Broad Line Radio Galaxies: Jet Contribution to the nuclear X-Ray Continuum

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ABSTRACT

It is shown that, for Broad Line Radio Galaxies the strength of the non-thermal beamed radiation, when present, is always smaller than the accretion flow by a factor < 0.7 in the 2-10 keV band. The result has been obtained using the procedure adopted for disentangling the Flat Spectrum Radio Quasar 3C 273 (Grandi & Palumbo 2004) Although this implies a significantly smaller non-thermal flux in Radio Galaxies when compared to Blazars, the jet component, if present, could be important at very high energies and thus easily detectable with GLAST.

Subject headings: galaxies: active galaxies —- X-rays: radio galaxies; jets

1. Introduction

The radio-quiet versus radio-loud dichotomy in Active Galaxies (AGNs) has been confuted by new deeper radio surveys which have revealed a continuous distribution of radio–loudness (White et al. 2000). Nuclear ejection of matter in the form of outflows and weak radio jets have also been observed in sources generally considered radio quiet AGNs (Ulvestad & Wilson 1984a, 1984b, 1989, Ulvestad et al. 2005, Kukula et al. 1995, Thean et al. 2001, Middelberg et al. 2004). Moreover the well consolidated nuclear correlation between X-ray and radio emission in powerful radio-loud sources has been recently extended to a larger sample of AGNs (Merloni et al. 2003, Maccarone Gallo & Fender 2003) including radio-quiet objects. This growing evidence in the recent literature has, therfore, put in a critical position the long debated idea that Active Galactic Nuclei are divided in two sharp classes. All these results are hinting towards a scenario in which accretion and ejected flows are closely related in all AGNs implying common physical mechanisms. Thus the fundamental question to address is how these mechanisms work under different physical conditions. In particular, the relation between the launch/quench of the jet and the disk accretion regime, is of primary importance.

Broad Line Radio Galaxies (BLRGs) are a key class for addressing this problem. Unlike blazars, the jet of these sources is not directly pointing towards the observer. Not completely blinded by non-thermal Doppler enhanced radiation, the observer can then attempt to look at both the accretion disk and jet. Moreover, unlike NLRG/HEGs (Hardcastle et al. 2006), BLRGs are not generally obscured by large amount of circumnuclear cold gas and, as a consequence, offer a direct view of their inner regions.

Although it is plausible that jets and disks are both present in BLRGs, results from detailed spectral X-ray studies are not conclusive (Grandi Malaguti & Fiocchi 2006; GMF06). GMF06 analyzed Beppo-SAX broad band spectra of 35 radio loud AGNs, 10 of which are BLRGs, and provide evidence of an anti-correlation between reflection line equivalent width (EW) and Radio Core Dominance (R) as expected if the beamed jet contribution is not negligible. However large errors from poor statistics cast some doubts on the robustness of the anticorrelation.

The present paper attempts to disentangle jet and disk in 3 Broad Line Radio Galaxies. The work was inspired by the 3C 273 results (Grandi & Palumbo, 2004) in which, separating jet from disk physical components, allowed a logical and self consistent picture to emerge for all the observed parameters of this blazar . In principle the approach, taken to tackle the problem in 3C 273, can be readily applied to other AGNs, provided data taken over a broad band (from 0.1 keV to at least 100 keV) and with sufficiently good statistics are available.

2. Extending the 3C 273 method to BLRGs

Analysis of BeppoSAX data of 3C 273 allowed to decouple the beamed non-thermal (jet) and unbeamed thermal (accretion flow) radiation produced in the inner region of a blazar. Previous approaches were phenomenological, i.e data were treated with “ad hoc”models in order to reproduce the observed X-ray spectra. The new analysis adopted a different starting-point. Data were fitted, having in mind a physical picture of the nuclear region. Thus, a black body, a cutoffed power law with a reflected component and an iron line, accounting for an accretion disk, plus a power law, reproducing a jet was attempted. The experiment, performed on different BeppoSAX observations of 3C 273, was successful and revealed a thermal component generally overwhelmed by non-thermal radiation by a factor of 1.2-3 in the 2-10 keV range and up to a factor of 7 above 20 keV.

The successive natural step has been to verify whether the same diagnostic approach could work for other radio loud AGNs. The best sources suitable for this test are 3C 120, 3C 382 and 3C390.3. Their BeppoSAX data cover a wide energy range and their spectra show continuum high energy cutoff and reprocessing features simultaneously observed (see GMF06).

In order to separate thermal (T, i.e. accretion flow) and non-thermal (NT, i.e. jet) contributions, detecting features over the continuum is essential. Indeed the model anchors to the cutoff energy, iron line equivalent width and reflection hump to estimate the jet contribution. After assuming that a disk emission is diluted by Doppler enhanced radiation. Furthermore it is implicitly assumed that the disk in BLRGs and Seyfert 1 galaxies produce similar continuum and reprocessing features (see later in Discussion).

No "physical" hypothesis was put forward for the soft component, observed in 3C 120 and 3C 382. Unlike the case of 3C 273, where a disk origin of the soft excess (below a few keV) is quite convincing, the nature of the soft photons in these sources is still uncertain (Zdziarski & Grandi 2001, Grandi et al. 2001, Ogle et al. 2005).

From the practical point of view, the following procedure was applied to each BLRG. The PEXRAV in XSPEC v11.1 and a gaussian line were used to fit the direct continuum and the reprocessed features of the accretion flow. The inclination angle (i) of the reflecting cold matter was always fixed to $i = 18°$ (cos $i = 0.95$). Although a different inclination angle can not be excluded in these radio galaxies, the face-on geometry was chosen to allow for a coherent comparison with the previous BeppoSAX survey results, not including the jet contribution. On the other hand, given the errors associated to the data (Table 5 of GMF06), an inclination angle change of about a factor 2 is included when we explore the range of parameters in Table 1. The line was assumed cold and narrow (energy peak and intrinsic width) in agreement with GMF06 results (see their Table 4). The accretion disk parameters were fixed to the average Seyfert 1 values, i.e Γ^T=1.79, E^T_{cut}=166 keV, $Ref^T = 0.75$ and $EW^T = 137$ eV deduced by a sample of 7 Seyfert 1 galaxies observed by BeppoSAX (see Table 5 of GMF06) and analyzed by Perola et al. (2002). The normalization (i.e the flux) was let free to vary. The jet was modeled with a power law. Spectral slopes (Γ^{NT}) of 1.5, 1.6, 1.7, 1.8 and 1.9 were tested. Each time, Γ^{NT} was fixed while the normalization (i.e the jet flux) was let free to vary. As discussed above, the soft component was not investigated. A simple "phenomenological" model was considered: a Raymond-Smith model and a power law were used for 3C 120 and 3C 382, respectively. In the case of 3C 382 when the presence of the jet model was investigated, a broken power law, rather than a double power law, was tested in order to minimize the number of free parameters. In 3C 120 and 3C390.3, known to be slightly obscured sources, a intrinsic column density (NH) was added in addition to the Galactic one.

A disk-jet model was considered acceptable (on the base of a F test) if statistically undistinguished or better than the model without a jet component (i.e that adopted in the BeppoSAX survey paper).

Finally, the same test was repeated for each minimum and maximum values of Γ^T, E^T_{cut}, Ref^T and EW^T defining the 1σ distribution spread reported in Table 5 of GMF (2006). In summary, 405 disk-jet possible configurations were considered as shown in Table 1.

3. Results

In spite of the wide grid of models tested, the successful trials are limited. These are shown in Table 2 with the ratio between thermal and non-thermal fluxes (T/NT) between 2-10 keV. The addition of a NT component always gives an acceptable fit. Although, the degrees of freedom of the model without the non-thermal component are larger, the χ^2 values are not significantly better than the disk-jet combination. In some cases, disk+jet fit gives χ^2/dof even smaller. Fits requiring $\Gamma^T \sim \Gamma^{NT}$ are not reported in Table 2. No useful information is contained in these trials. They simply split the continuum photons in two very similar power laws, thus imitating the "phenomenological" model.

3C 120 – The 3C 120 data allow 9 different jet-disk configurations. All require a low energy cut-off ($E^T_{cut} = 93$ keV), quite steep thermal power law ($\Gamma_T = 1.79 - 1.93$) and two possible values of the iron line equivalent width (EW^T=90-136 eV). When the reflection and the iron lines are weak only upper limits ($NT/T < 0.4$) of the jet strength can be obtained (see 1-4 rows in Table 2). On the contrary, when stronger iron lines and reflection humps are assumed, the jet contribution to the X-ray continuum is well constrained. It is of the order of $\sim 20 - 40\%$, depending of the slope of the non-thermal power law. The strength of the non-thermal component increases with the steepening of Γ^{NT} . Note that the spectral feature which more strongly constrains the jet-disk configuration is the high energy cutoff.

3C 390.3 – In this source, the Doppler enhanced non-thermal radiation requires a flat spectral slope ($\Gamma_{NT} = 1.4 - 1.6$) and a NT/T flux ratio in the 2 -10 keV ranging from 0.1-0.7 (taking into account the flux ratio uncertainties). Also in this case the jet contribution to the X-ray continuum can not be larger than 40%.

Table 1. Model Tested[a]

Thermal/Accretion Model (T)				Non-Thermal/Jet Model (NT)
Γ^T	E^T_{cut} (keV)	Ref^T	EW^T (eV)	Γ^{NT}
1.79	166	0.75	137 [93, 266]	1.5-1.9
1.79	166	0.45	137 [93, 266]	1.5.1.9
1.79	166	1.05	137 [93, 266]	1.5.1.9
1.79	93	0.75	137 [93, 266]	1.5-1.9
1.79	93	0.45	137 [93, 266]	1.5.1.9
1.79	93	1.05	137 [93, 266]	1.5.1.9
1.79	239	0.75	137 [93, 266]	1.5.1.9
1.79	239	0.45	137 [93, 266]	1.5.1.9
1.79	239	1.05	137 [93, 266]	1.5.1.9
1.65	166	0.75	137 [93, 266]	1.5-1.9
1.65	166	0.45	137 [93, 266]	1.5.1.9
1.65	166	1.05	137 [93, 266]	1.5.1.9
1.65	93	0.75	137 [93, 266]	1.5-1.9
1.65	93	0.45	137 [93, 266]	1.5.1.9
1.65	93	1.05	137 [93, 266]	1.5.1.9
1.65	239	0.75	137 [93, 266]	1.5.1.9
1.65	239	0.45	137 [93, 266]	1.5.1.9
1.65	239	1.05	137 [93, 266]	1.5.1.9
1.93	166	0.75	137 [93, 266]	1.5-1.9
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1.93	93	1.05	137 [93, 266]	1.5.1.9
1.93	239	0.75	137 [93, 266]	1.5.1.9
1.93	239	0.45	137 [93, 266]	1.5.1.9
1.93	239	1.05	137 [93, 266]	1.5.1.9

[(a)]Each row represent 15 different disk-jet configurations, obtained considering 3 Fe EW (the average value [minimum,maximum]) and 5 spectral slopes of the jet (Γ^T=1.5, 1.6, 1.7, 1.8, 1.9)

Table 2. Fit Results

Source	Γ^T	Thermal/Accretion Model (T) E^T_{cut} (keV)	Ref^T	EW (eV)	Non-Thermal/Jet Model (NT) Γ^{NT}	Flux ratio NT/T (2−10 keV)	χ^2/d.o.f. With NT	χ^2/d.o.f. Without NT
3C 120	1.79	93	0.45	90	1.4	< 0.09	132/133	129/130
	1.79	93	0.45	90	1.5	< 0.1	133/133	129/130
	1.79	93	0.45	90	1.6	< 0.2	133/133	129/130
	1.93	93	0.75	136	1.5	$0.3^{+0.1}_{-0.1}$	135/133	129/130
	1.93	93	0.75	136	1.6	$0.5^{+0.3}_{-0.3}$	135/133	129/130
	1.93	93	1.05	136	1.4	$0.2^{+0.1}_{-0.1}$	135/133	129/130
	1.93	93	1.05	136	1.5	$0.2^{+0.1}_{-0.1}$	133/133	129/130
	1.93	93	1.05	136	1.6	$0.4^{+0.1}_{-0.1}$	131/133*	129/130
	1.93	93	1.05	136	1.7	$0.7^{+0.1}_{-0.1}$	134/133	129/130
3C 390	1.79	166	0.75	136	1.4	0.3±0.1	125/120	124/117
	1.79	166	0.75	136	1.5	0.4±0.2	128/120	124/117
	1.79	166	1.05	136	1.4	0.2±0.1	122/120*	124/117
	1.79	166	1.05	136	1.5	0.3±0.2	123/120	124/117
	1.79	166	1.05	136	1.6	0.4±0.3	128/120	124/117
	1.79	93	0.75	136	1.4	0.4±0.1	128/120	124/117
	1.79	166	0.75	90	1.4	0.3±0.1	131/120	124/117
3C 382	1.79	93	0.45	90	^{a}1.5	0.13±0.04	149/149	138/146
	1.79	93	0.45	90	^{a}1.6	0.5±0.2	146/149	138/146
	1.93	93	0.75	90	^{a}1.5	0.3±0.1	149/149	138/146
	1.93	93	0.75	90	^{a}1.6	0.5 ±0.1	142/149	138/146
	1.93	93	0.75	90	^{a}1.7	1.0 ±0.3	145/149	138/146
	1.93	93	1.05	90	^{a}1.7	0.8 ±0.3	143/149	138/146
	1.93	166	0.75	90	^{a}1.7	0.7±0.2	147/149	138/146
	1.93	93	0.75	90	^{a}1.7	1.1±0.3	149/149	138/146
	$1.8^{+0.1}_{-0.6}$	85^{+142}_{-25}	$0.5^{+0.5}_{-0.3}$	$^c38^{+37}_{-36}$	$^b1.5^{+0.9}_{-0.4}$	$0.2^{+0.5}_{-0.2}$	135/145*	138/146

$^{(a)}$The soft slopes ($\Gamma_{\rm soft}$) of the broken power law range between 2.1-2.7. The energy breaks ($E_{\rm break}$) are between 2.2 and 3.0 keV

$^{(b)}\Gamma_{\rm soft} = 2.7^{+0.5}_{-0.6}$, $E_{\rm break} = 2.8^{+2.0}_{-0.8}$

$^{(c)}$The Fe equivalent width is calculated considering only the thermal X-ray continuum

$^{(\star)}$Disk-jet configurations with the smallest χ^2 values

3C 382 – The soft excess of this source is rather complex. However it can be simplified by adopting a pure power law. As discussed when the jet component is also taken into account a broken power law is introduced. The successful models are reported in Table 2. The most relevant result here is that, in spite of the jet powerful $NT/T = 0.1 - 1.1$, the iron line is forced to its minimum permitted value (EW^T=90 eV).

Finally, it should be noted that, unlike the other 2 BLRGs, for 3C 382 one can estimate the jet power fixing "a priori" all the spectral parameters (last row in Table 2). Obviously, the uncertainties are large and include all the previous disk-jet configurations. The only exception is the Fe equivalent width, which, being smaller than 90 eV, confirms the extreme weakness of the reprocessed feature in this source.

4. Discussion

On the bases of the BeppoSAX results one cannot exclude that a non-thermal component is present in BLRGs. Actually the fits obtained for 3C 120 3C390.3 and 3C 382 show that the data are consistent with a combination of a thermal component (in a first approximation associated with an accretion disk) and a non-thermal component to be associated with beamed radiation (i.e a jet). However the jet contribution is not large and the accretion flow emission in the 2-10 keV range ($NT/T < 0.7$) is always dominant. In 3C 382 a very powerful jet ($NT/T > 1$) is statistically permitted by the model. However its contribution to the X-ray continuum becomes ($NT/T \leq 0.7$), matching the other BLRG values, as soon as the disk-jet spectral parameters are let free to vary. 3C 382 provides further information. Its Fe feature is weak even if a jet is included to fit the data. This implies that the production of features by a disk and/or a dusty torus is really inefficient, suggesting that a dilution of the X-ray continuum due to a Doppler enhanced radiation is not the main cause of the Fe line shrinking.

The successful trials in Table 2 display generally hard non-thermal spectral slopes ($\Gamma^{NT} \sim 1.5 - 1.7$). Thus the jet of these BLRGs could be in the Inverse-Compton regime. This sounds promising. Indeed in the Spectral Energy Distributions (SED) of these radio galaxies (Figure 1) there is a bump in the mm-infrared band which could hide the low energy synchrotron peak. Although part of the infrared radiation is probably a mix of thermal (from cold/dusty matter) and non-thermal radiation, this peak associated to the jet X-ray spectrum undoubtedly recalls the synchrotron-Inverse Compton SED of a blazar.

Although the observed X-ray photons in the 2-10 keV band are produced at most in an accretion flow, the jet, if present, is expected to prevail over the thermal radiation above

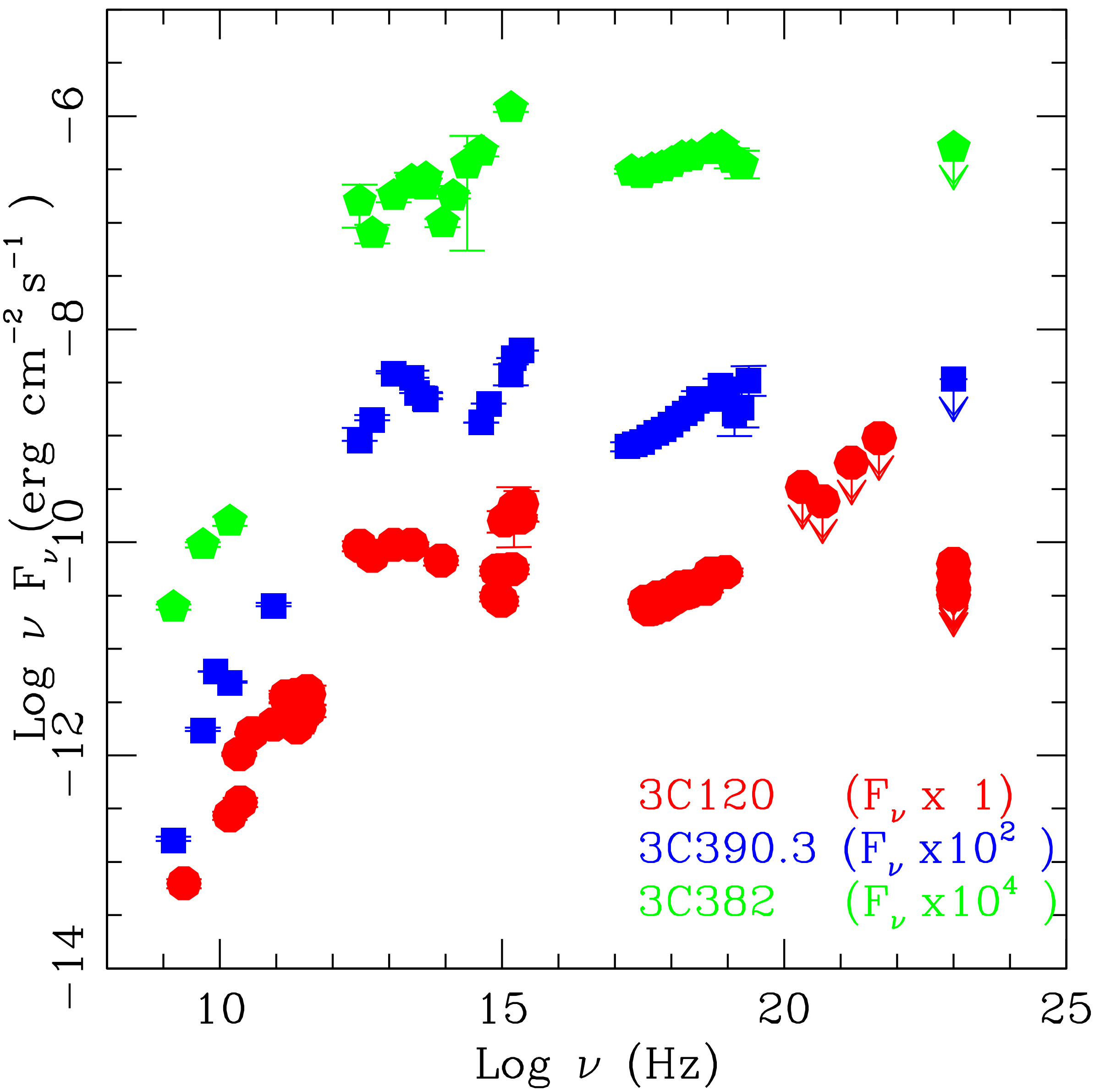

Fig. 1.— Spectral Energy Distribution of 3C 120, 3C390.3 and 3C 382. With the exception of the BeppoSAX data (this paper), the SED points are from literature: Bloom et 1994, Chiaberge et al.2002, Clavel et al. 2000, Hardcastle et al. 1999, Lilly & Longair 1985, Knapp et al.1991, Mc Alary et al. 1979,Maisack et al. 1997, Maraschi et al. 1991, Morganti et al. 1997, Robson et al. 2001, Rudnick et al. 1996,Schachter & Elvis 1994, Steppe et al. 1990, 1991, Tadhunter et al.1986, Von Montigny et al. 1995, Zirbel et al. 1993.Optical–UV data are corrected for Galactic/Intrinsic reddening (Cardelli et al. 1989) assuming the BeppoSAX column density N_H.

100-200 keV. Indeed, at high energies, the accretion flow power law drops and the jet should emerge. The successive immediate question to address is: are the jets in BLRGs bright enough to be directly observable at high energies? In order to verify it, we extrapolated the jet-disk models up to GeV energies. For each BLRG, we considered as the most probable description of the data, the model in Table 2 with the smallest χ^2 value (indicated with $\star$). It appeared immediately evident that the jet spectrum has to bend before reaching the GeV region to respect the EGRET upper limit constraint (see Figure 2). This is not surprising. The 3C 273 beamed component, which has been actually detected by both the Comptel (Von Montigny et al. 1996) and EGRET (von Montigny et al. 1993) instruments on-board of the GRO satellite, shows exactly that spectral shape. Taking advantage from this, the Compton peak and the GeV emission of each radio galaxy was reconstructed following the 3C 273 curvature. In details, the non-thermal 100 keV flux density of 3C 273 was divided by each BLRG and the ratio used to rescale the 3C 273 spectrum to the jet emission of the three Radio Galaxies. The results are shown in Figure 2, where the MeV-GeV extrapolated fluxes of each radio galaxy are drawn as open circles. Although BLRG are less luminous by about a factor 10 than 3C 273, their non-thermal radiation will become easily detectable for telescopes of the near future. In Figure 2 the GLAST integral sensitivity curve[1] rescaled to 55 days of observation is shown (solid blue line). Even considering a very pessimistic reduction by a factor 2 of the on-flight GLAST performance (dotted blue line), we conclude that less than 8 weeks should be sufficient for GLAST to reveal radio galaxies with fluxes of order $F_{E>100MeV} = 4 \times 10^{-8}$ phots $cm^{-2}s^{-1}MeV^{-1}$.

5. Conclusion

A new interpretation of the BLRGs spectra observed by BeppoSAX is discussed. The method successfully applied to the Blazar 3C 273 (Grandi & Palumbo 2004) to disentangle the jet and disk components has been used. Following this approach for 3C 120, 3C390.3 and 3C 382, we conclude that:

- Beamed non–thermal X–ray continuum does not significantly contaminate the nuclear emission of these sources. The jet, if present, does not contribute more than 45%.

- The iron line is weak even taking into account the presence of a non-thermal beamed radiation, at least in 3C 382. If confirmed by other BLRG observations (e.g. the Suzaku satellite), other physical reasons rather than the jet presence, have to be invoked.

[1] http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm

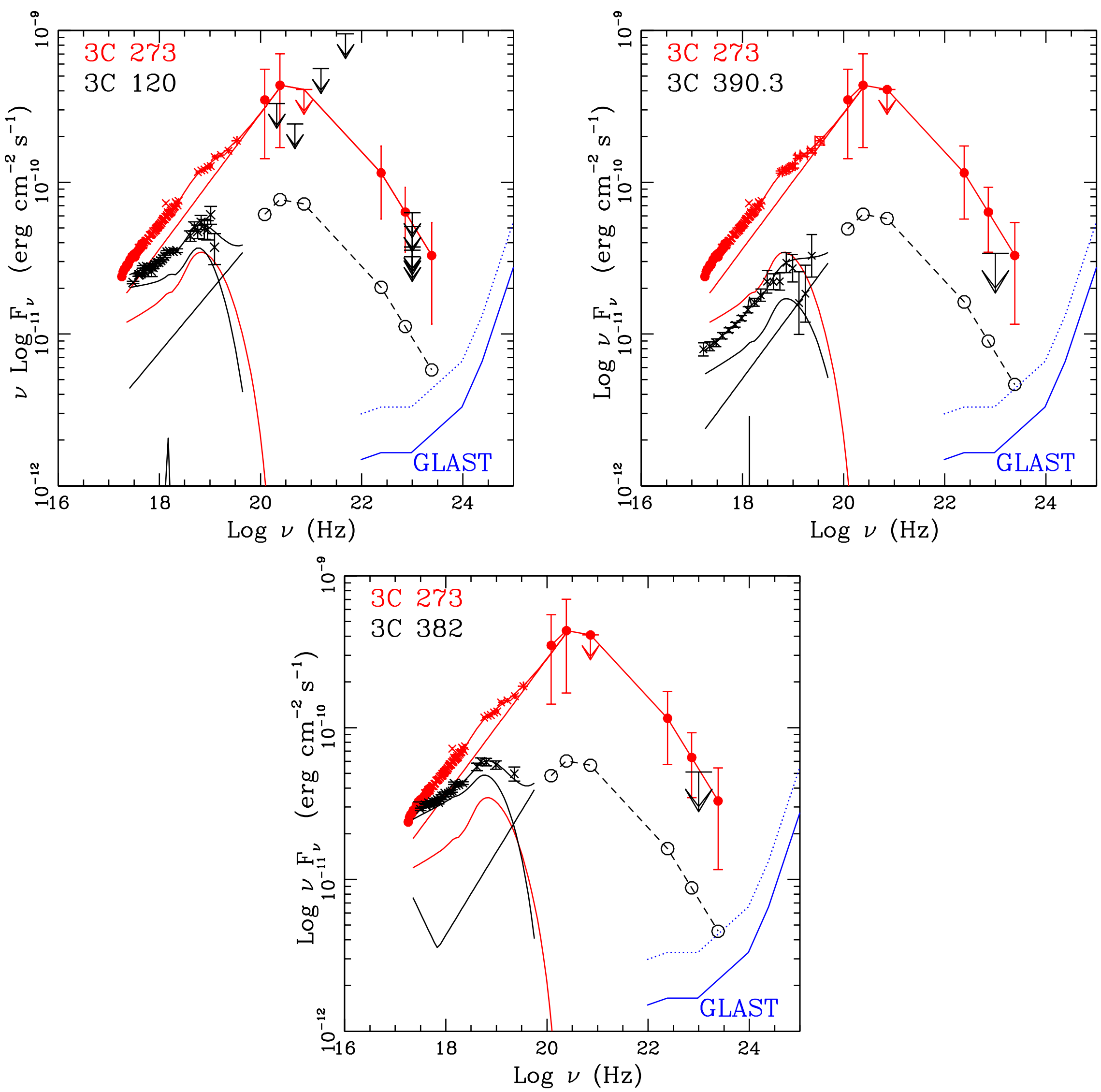

Fig. 2.— BeppoSAX BLRG (black) and 3C 273 (red) data (EGRET data from Turler et al. 1999) fitted with a combination of accretion flow and jet models (solid lines). Open circles represent the jet extrapolation to high energies, assuming a 3C 273 spectral shape. Black dotted lines are point interpolations. 3C 120 (left panel), 3C390.3 (right panel) and 3C 382 (lower panel) will be all detectable by GLAST. Solid blue line represents the 55 days GLAST integral sensitivity curve. Even considering a less optimistic sensitivity curve, rescaled by a factor 2 (dotted blue line), BLRG jets should be detected by GLAST

For example, assuming that the disk is thin but optically thick, less prominent iron lines could be explained within a light bending model as proposed by Miniutti & Fabian 2004. Alternatively one can assume that in radio-galaxies the accreting gas is characterized by low radiative efficiency (at least in the inner regions) and explain the weak line as due to small solid angle subtended by the cold matter (i.e external disk region and/or torus) to the primary X-ray source (GMF06 and references therein).

- The SEDs of powerful BLRGs likely hide a jet with a spectral shape very similar to that of 3C 273. The infrared bump of radio galaxies recalls the synchrotron peak of blazars and the quite hard spectral slope of their simulated jet, a non-thermal inverse Compton emission. If this is the case, these BLRGs are expected to be less luminous than 3C 273 by about a factor 10 in the MeV-GeV regions. In spite of that, 3C 120, 3C390.3 and 3C 382 are very promising targets for the GLAST mission

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